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INVESTIGATION OF METHODS TO PREDICT THERMAL STRATIFICATION AND --ETC(U)
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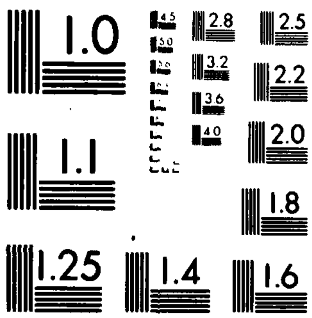

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SPECIAL REPORT E-160
May 1980
(Thermal Stratification)

INVESTIGATION OF METHODS TO PREDICT THERMAL STRATIFICATION AND ITS EFFECT ON SOLAR ENERGY SYSTEM PERFORMANCE

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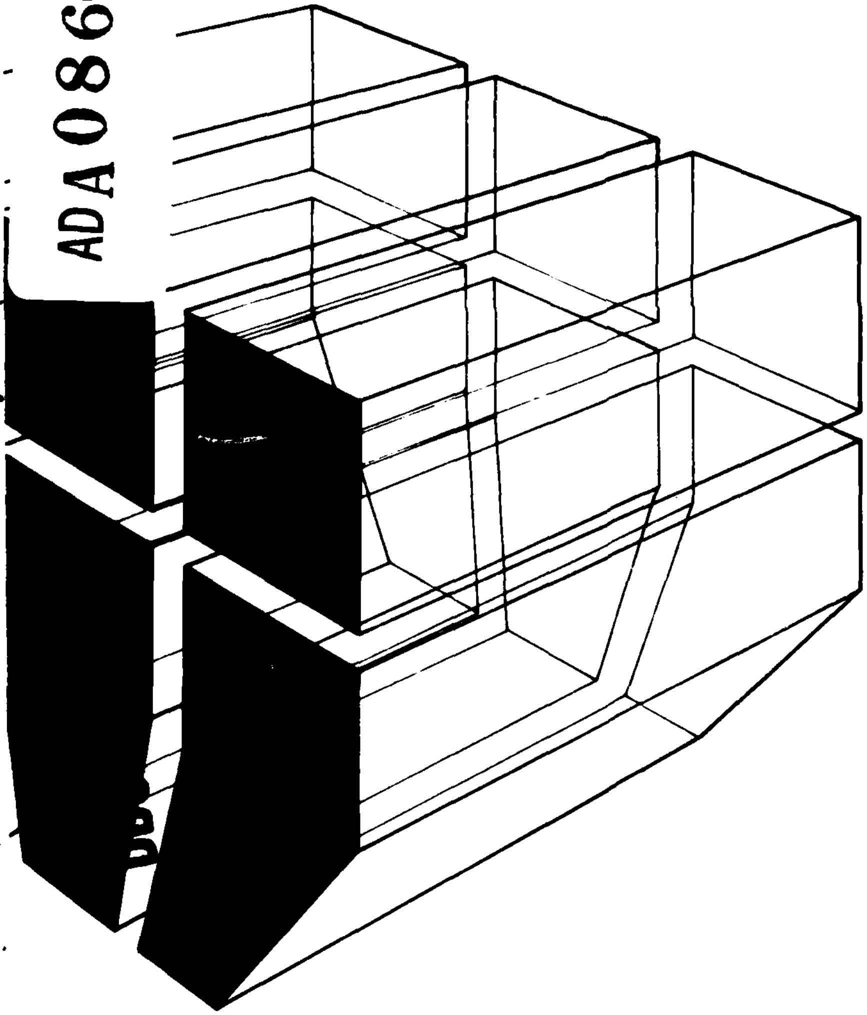

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This report describes a study to identify characteristics which induce thermal stratification in liquid thermal storage, and to evaluate solar energy system performance as a function of the degree of stratification.

It was determined that for efficient use of thermal stratification it was necessary to (1) introduce hot fluid at the top of the liquid

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storage tank and to add cold fluid at the bottom of the tank, (2) with a cylindrical tank, have a length/diameter ratio $>$ 2.0, (3) use mathematical correlations to determine allowable fluid inlet velocities and temperatures, and (4) use storage tank material that has a thermal conductivity less than that of the storage fluid.

The mathematical correlations described in this report allow stratification occurrence to be predicted and can be used to estimate the sharpness of the thermocline based on tank inlet and outlet conditions, fluid properties, and storage tank geometry.

FOREWORD

This work was performed for the Office of the Chief of Engineers (OCE), under Project 4A761102AT23, "Basic Research in Military Construction"; Task B, "Engineering Systems"; and Work Unit 010, "Thermal Stratification."

The work was performed by the Energy Systems Division (ES), U.S. Army Construction Engineering Research Laboratory (CERL). Mr. R. Donaghy is Chief of ES.

Appreciation is expressed to Mr. George Walton of CERL for his assistance in system simulations.

COL Louis J. Circeo is Commander and Director of CERL and Dr. L. R. Shaffer is Technical Director.

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1 INTRODUCTION

Background

The high costs of conventional and alternate energy sources require that they be used efficiently; one way of insuring energy efficiency and conservation is to store excess energy for later use. Energy storage is sometimes a matter of physical necessity, as in solar energy systems, and sometimes a matter of economic necessity, as when electric utilities offer a peak billing program.

Because much of the energy consumed today exists at one time or another as thermal energy, there is an increasing use of and need for thermal energy storage.

Thermal energy may be stored in various ways: (1) as sensible heat by increasing of a material's temperature, (2) as latent heat by changing the phase of a material (i.e., melting, boiling), or (3) as a combination of (1) and (2).

Because sensible heat storage is simple and inexpensive, it is currently the most common energy storage method; the materials most often used to store energy as sensible heat are water and rock. Sensible storage also sometimes allows temperature stratification, which may improve the performance of systems using the sensible heat storage method.[1]

Objective

The objective of this report is to identify characteristics which induce stratification in liquid thermal storage, and to evaluate energy system performance as a function of the degree of stratification.

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[1] T. D. Brumleve, Sensible Heat Storage in Liquids, Plowshare and Transducer Technology Division 8184, Report SLL-73-0263 (Sandia Laboratories, July 1974).

Approach

An experimental apparatus was designed and constructed to evaluate the impact of inlet/outlet conditions, fluid properties, and tank geometry on the fluid temperature profile. Experiments and analyses were performed based on correlating experimental data with previously identified dimensionless parameters.[2] In addition, several literature searches were undertaken. Based on the results of the experiments and the available literature, a computer simulation of a solar energy system was performed.

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[2] A. Cabelli, "Storage Tanks, a Numerical Experiment," Solar Energy, Vol 19, No. 1 (Pergamon Press, Inc., 1977), pp 45-54.

2 CHARACTERISTICS WHICH INDUCE STRATIFICATION

Definition of Thermal Stratification

Thermal stratification exists in storage fluid when there is a temperature differential between top and bottom fluids. This temperature differential is caused by buoyant forces resulting from the density difference between hot and cold fluid.

This definition is quite broad and would include all the conditions shown in Figure 1. In fact, the buoyant forces are so pervasive that some degree of stratification exists in almost all storage, except for storage with very large mixing forces.

Figure 1a shows the components of stratified storage as it was defined for this study. There is a hot mixed layer, a cold mixed layer, and a boundary region (thermocline) separating the hot and cold mixed layers. The lower limit of stratification is reached when the thermocline occupies the entire tank (Figure 1b). Figures 1c and 1d show partially and fully mixed conditions.

Characteristics Which Induce Stratification

The phenomenon of thermal stratification in thermal storage is complex. The important elements of the thermal stratification problem are: buoyant forces, mixing forces, thermal diffusivity, thermal conductivity, inlet configurations, and tank geometries. Also important are the variations of some of these elements with time as storage is used in a system.

The results of the research to date indicate that, in general, the following elements enhance stratification:

1. Warm fluid inlet at top, cold fluid inlet at bottom

2. Increasing the temperature differential between tank fluid and incoming fluid

3. Reducing the inlet fluid velocity

4. Decreasing the tank wall conductivity

5. Increasing the L/D ratio

where:

L = length of cylindrical tank (m)

D = diameter of cylindrical tank (m).

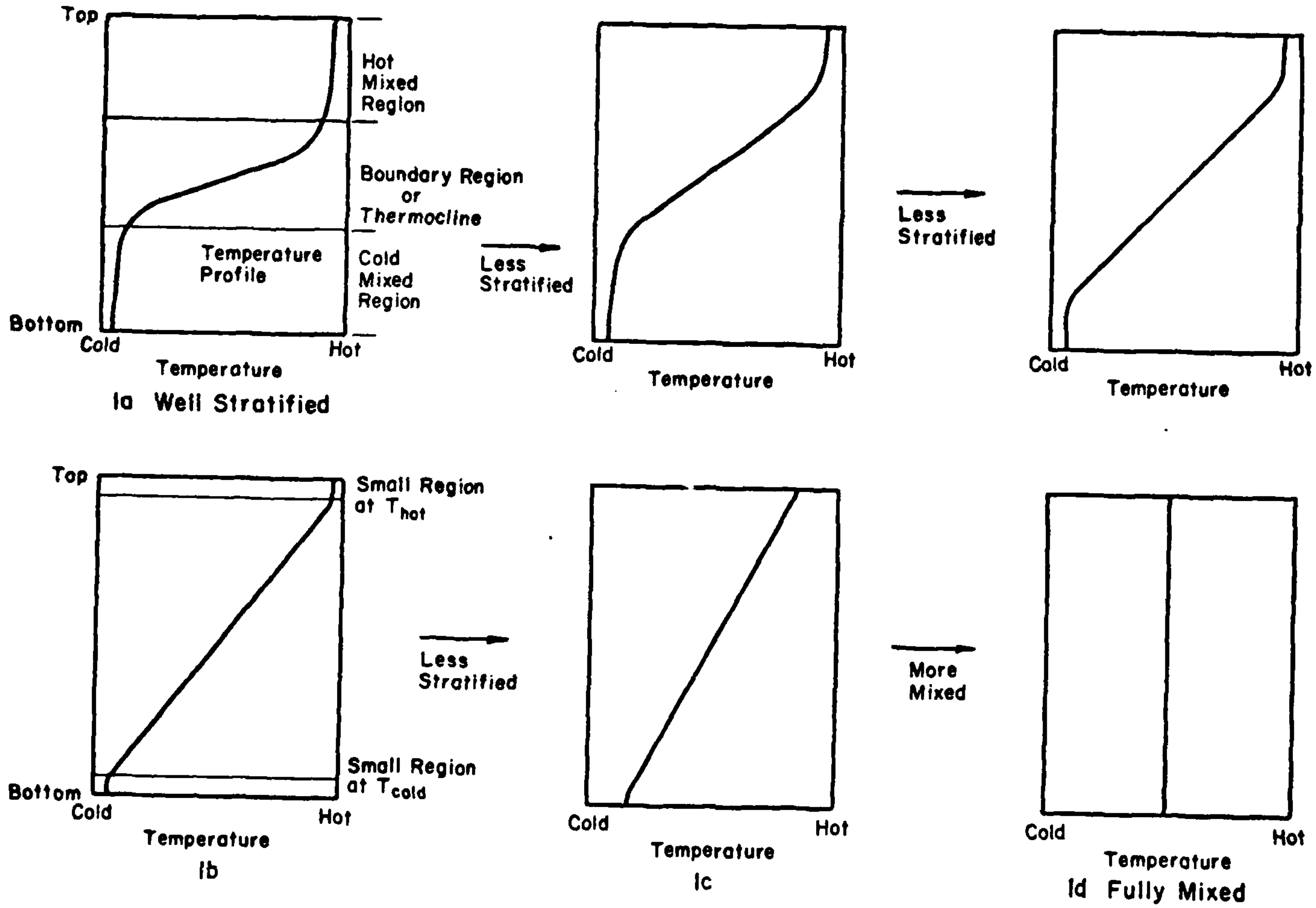

Figure 1. Examples of temperature profiles.

Effects of Inlet Temperatures, Velocities, and Tank L/D Ratio

There are two correlations available which predict the occurrence of storage stratification as a function of operating temperatures, inlet velocities, and tank dimensions. The correlations were developed concurrently by different methods, but they are very similar. Both of the correlations are based on experimental data gathered under the following conditions:

1. Constant ΔT between inlet fluid and tank fluid
2. Constant flow rate
3. Well-insulated tanks with low tank-wall conductivity.

The first of these correlations is that proposed by Lavan and Thompson.[3] In their experiments, a cylindrical plexiglass tank was filled first with hot water at 105°F (40.6°C), then with cold water at 60°F (15°C), which was pumped into the tank through a horizontal inlet at the bottom of the tank. This corresponds to the condition of discharging energy from the tank. As cold fluid displaced hot fluid in the tank, the exit fluid temperature was measured. To quantify their results, Lavan and Thompson introduced an extraction efficiency defined as:

$$\eta = Q \cdot t/V \qquad \text{[Eq 1]}$$

where:

η is the extraction efficiency (dimensionless)
Q is the volumetric flow rate
V is the tank volume
t is the time it takes the initial inlet/exit temperature difference as measured at the exit to drop some preassigned value.

In these experiments, a 10 percent drop was assumed, i.e.:

$$\text{At time } t, \left(\frac{T_{out} - T_{initial}}{T_{in} - T_{initial}}\right) = 0.9 \qquad \text{[Eq 2]}$$

Various experiments were performed with different values of L/D, ΔT, and inlet velocity. The results are summarized in Figure 2.

[3] Z. Lavan and J. Thompson, "Experimental Study of Thermally Stratified Hot Water Tanks," Solar Energy, Vol 19, No. 5 (1977), pp 519-524.

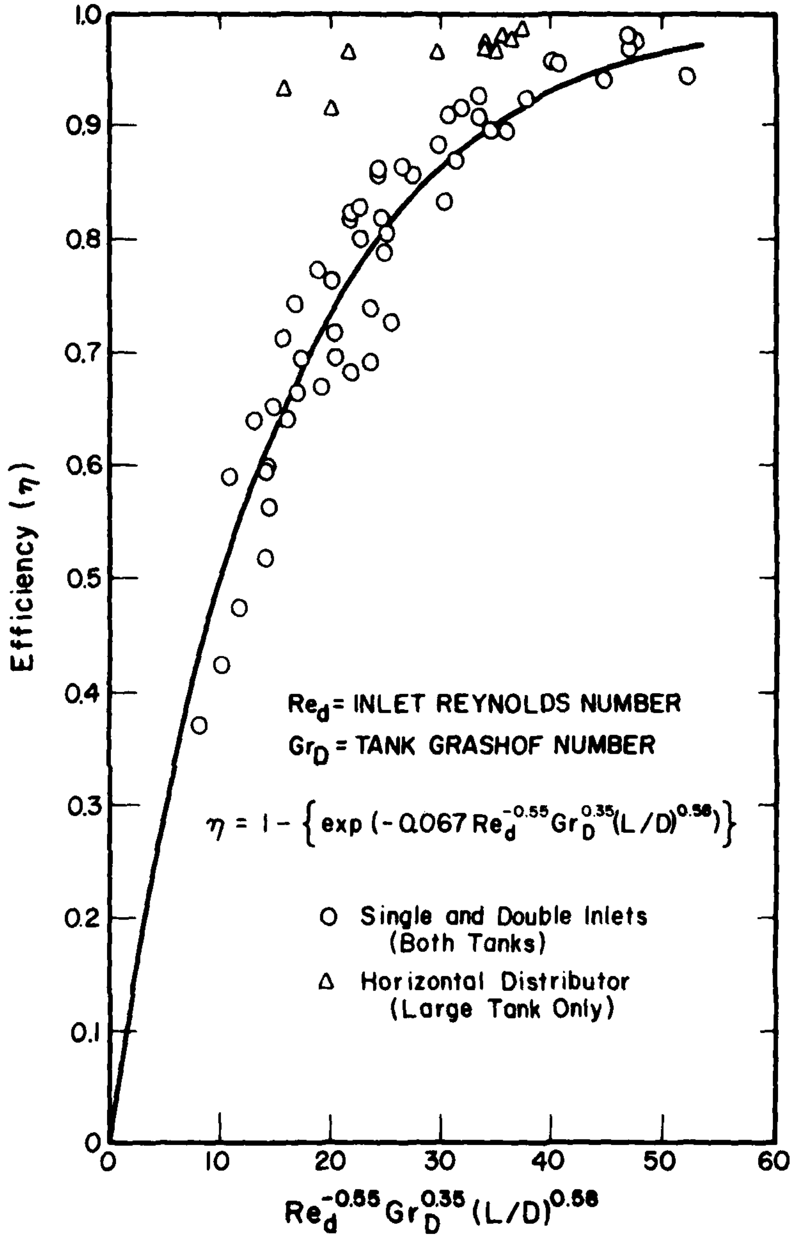

Figure 2. Results of work by Lavan and Thompson.
(Reprinted with permission from [Solar Energy, Vol 19, Figure 9 of "Experimental Study of Thermally Stratified Hot Water Tank," by Z. Lavan and J. Thompson], Copyright [1977], Pergamon Press, Ltd.)

The data points indicated by Δ in Figure 2 were taken using a horizontal distributor constructed of 0.7 in. (17.7 mm) diameter copper tubing with fifty 0.112-in.- (2.84-mm)-diameter holes drilled in two lines along the tube on a 0.25-in. (6.35-mm) center. Figure 2 shows the improvement in extraction efficiency obtained with the distributor. A second correlation was developed based on data from a previous study[4] and data gathered during this study. This correlation was developed by observing the temperature profile along the center line of a cylindrical fiberglass tank with an L/D of 2. The inlets and outlets were horizontal and made of 1/4- and 1/2-in. (6.35- and 12.7-mm) schedule 40 steel pipe. Experiments were performed under conditions of charging and discharging. In the charging experiments, the tank was filled initially with water ranging in temperature from 70 to 150°F (21 to 65°C). Warmer fluid was then pumped in at the top of the tank as cooler fluid was removed at the bottom. The differential between inlet fluid temperature and initial tank temperature ranged from 10 to 50°F (5.56 to 27.78°C). Flow rates ranged from 0.2 to 1.5 gpm (0.76 to 5.68 ℓ/min).

In the discharging experiments, the initial tank temperature ranged from 80 to 135°F (26 to 57°C). In the discharging experiments, cooler fluid was pumped in at the bottom of the tank. The differential between the inlet and initial tank fluid temperature ranged from 10 to 70°F (5.56 to 38.89°C). The apparatus used in these experiments is shown in Figure 3.

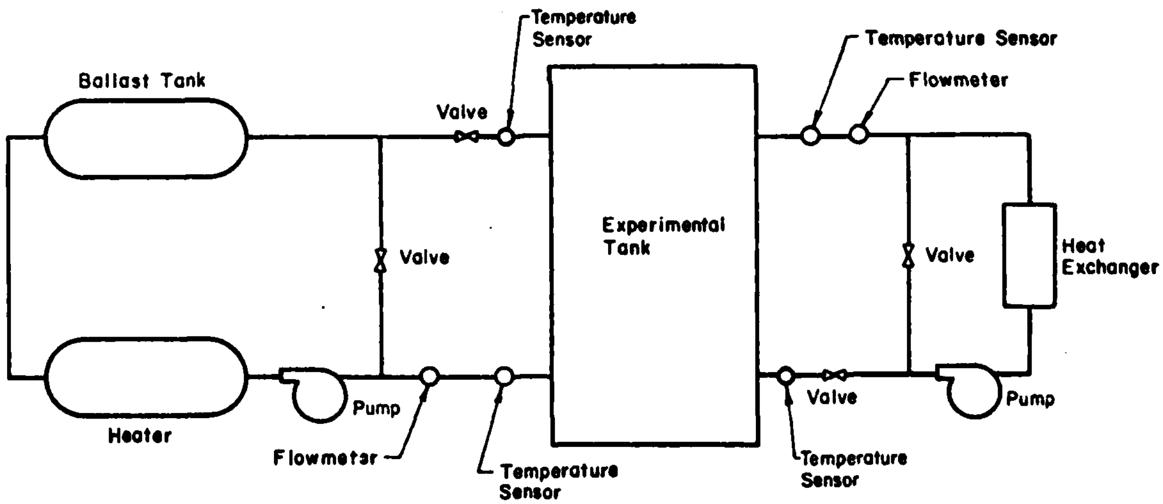

Figure 3. Experimental apparatus.

[4] B. Sliwinski, A. Mech, and T. S. Shih, "Stratification in Thermal Storage During Charging," Proceedings, Sixth International Heat Transfer Conference, Vol 4 (Toronto, Canada, 1978), pp 149-154.

The temperature profiles observed in these tanks indicated that the depth at which the thermocline formed varied from experiment to experiment. Therefore, the depths at which thermoclines formed were used to quantify the occurrence of stratification. Figure 4 shows some of the profile types observed during the experiments. The dimensionless mixing parameter

$$L^*/L \qquad \text{[Eq 3]}$$

is introduced where L* is the depth where the thermocline forms and L is the distance between the inlet and outlet.

The parameter L*/L was correlated with a dimensionless parameter known as the Richardson number. This number is a ratio of buoyant to mixing forces:

$$Ri = \frac{g \beta \Delta T_o L}{v_i^2} \qquad \text{[Eq 4]}$$

where:

Ri = Richardson number
g = acceleration of gravity (m/s^2)
β = volume expansivity ($1/^oC$)
v_i = inlet velocity (m/s)
ΔT_o = difference between inlet fluid and initial tank fluid temperature (^oC).

This correlation is shown in Figure 5.

When L*/L = 1.0, the tank is fully mixed; when L*/L = 0.0, stratification occurs immediately at the inlet of the tank.

Limits to Present Correlations

The correlations described previously improve the designer's ability to predict stratification, but they have limitations. The most important limitation is the inability to predict the effect of varying input temperature on the fluid temperature profile. Preliminary experiments were performed to study the effect of varying inlet temperatures. The results of these preliminary experiments are shown in Figure 6.

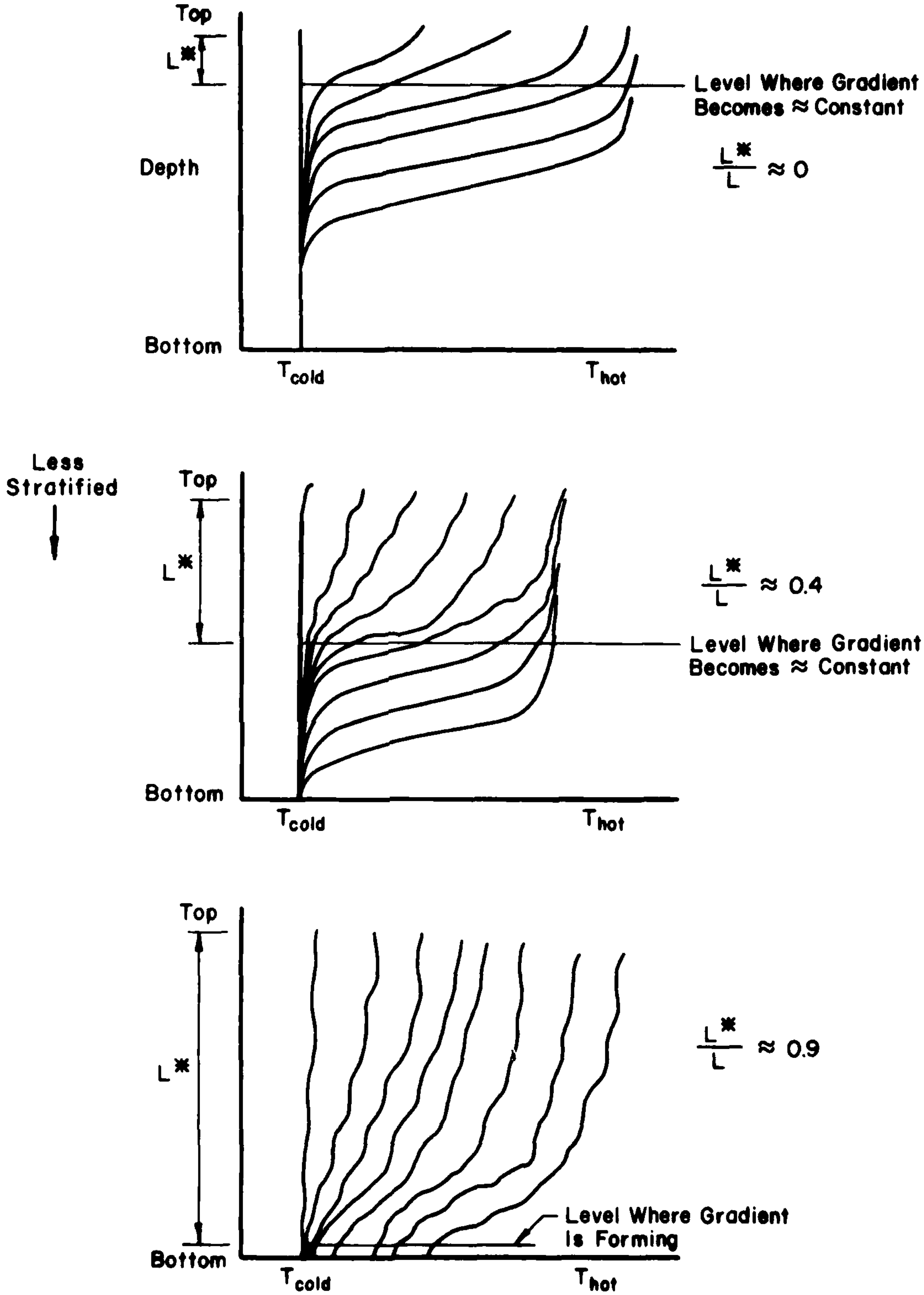

Figure 4. Examples of the types of profiles observed experimentally.

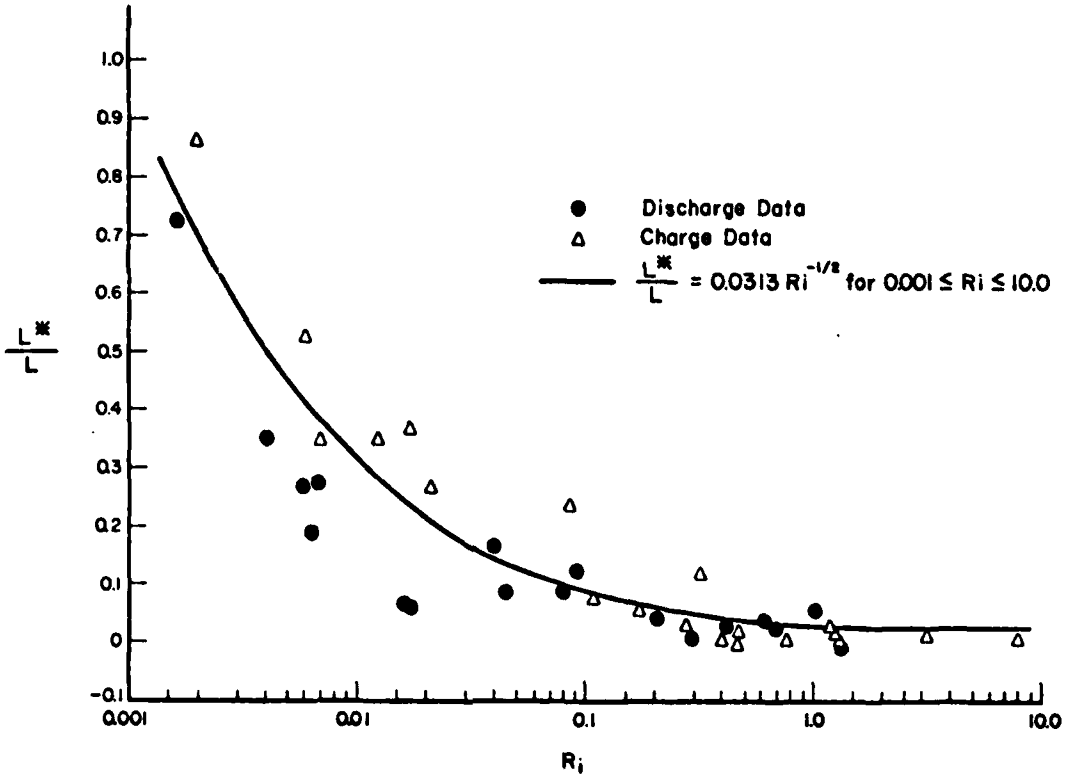

Figure 5. Occurrence of stratification as function of Ri.

Sharpness of Thermocline

The sharpness of the thermocline characterizes the degree of stratification. The sharpness can be used to predict thermal tank material stresses. The sharpness of thermocline is given by

$$\Delta T/\Delta Z/\Delta T_0/L \qquad \text{[Eq 5]}$$

where:

ΔZ is the thickness of the linear portion of the thermocline
ΔT is the temperature difference across the linear portion of the thermocline (Figure 7).

Eq 5, correlated with the Richardson number is:

$$Ri_D = \frac{g\beta\Delta T_0 L}{V_D^2} \qquad \text{[Eq 6]}$$

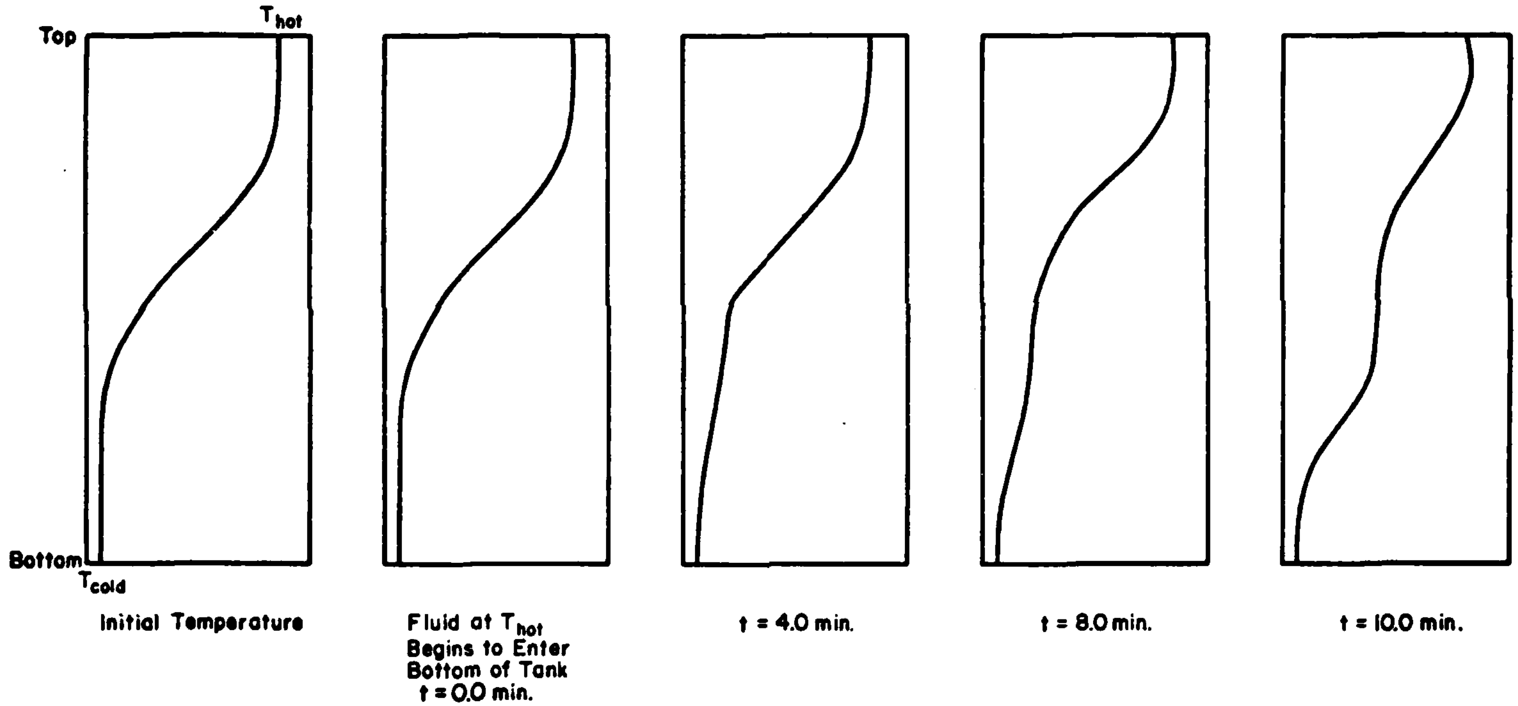

Figure 6. Effects of hot fluid entering at bottom of stratified fluid.

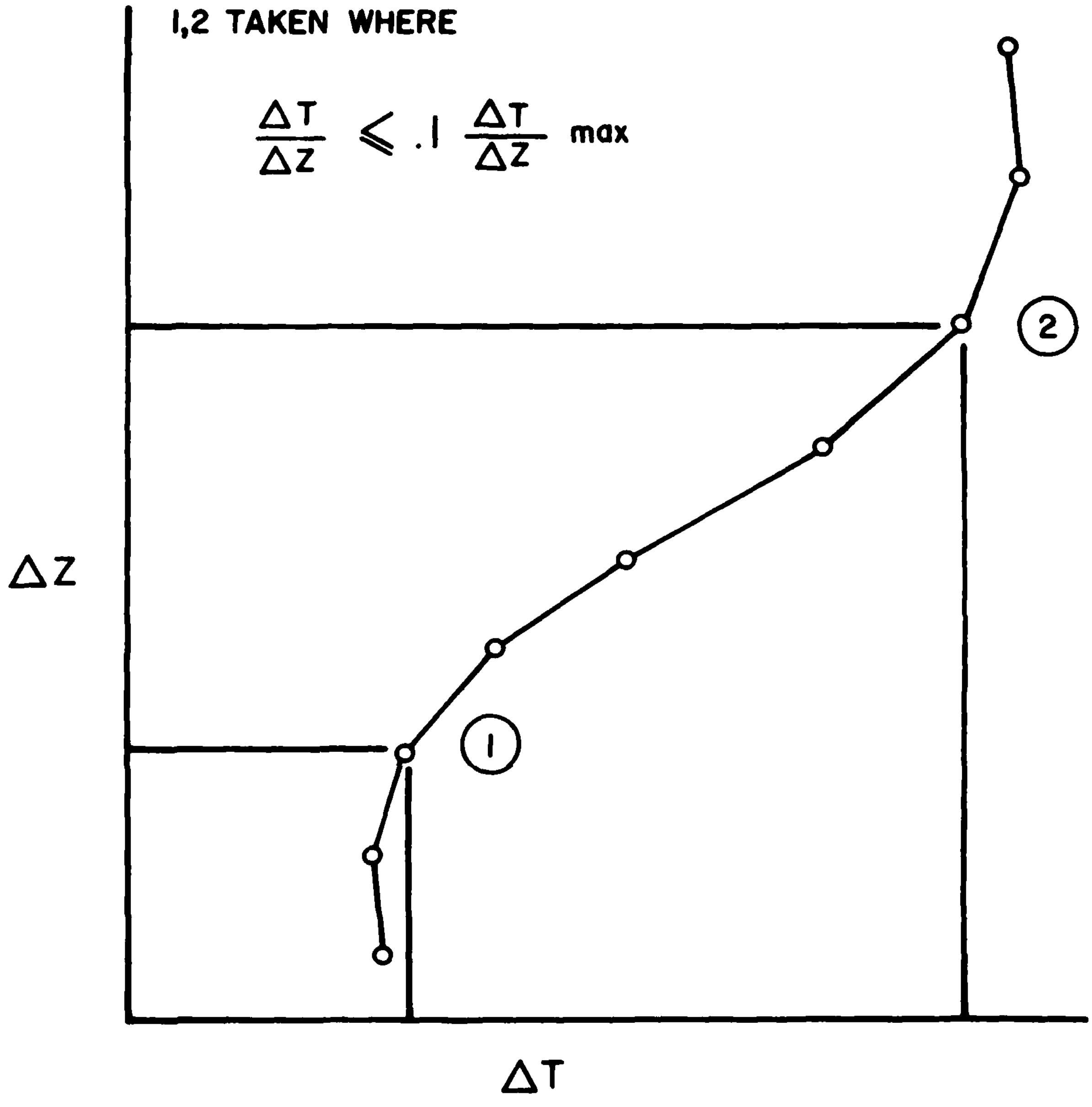

Figure 7. Choice of ΔT/ΔZ.

and with the Peclet number defined as:

$$Pe = Re_D Pr \qquad \text{[Eq 7]}$$

where:

Re_D is the Reynolds number based on the tank diameter
Pr is the Prandtl number

The Peclet number is the ratio of heat transfer by convection to heat transfer by conduction. These correlations are shown in Figures 8 and 9.

At this time it is difficult, based on the scantiness of the data, to place a high degree of confidence in these correlations. However, as a guide to estimating the sharpness of the thermocline, $\Delta T/\Delta Z/\Delta T_o/L$ ranged from 8 to 3, with an average from all experiments of 4.09, and a standard deviation of 1.23.

Effect of Tank Wall Conductivity on Thermal Stratification

The decay of the thermocline is a function of the conduction between the hot and cold layers through the fluid and through the tank wall. When the tank wall has a thermal conductivity higher than that of the fluid, the wall conduction effects can be 6 to 7 times larger than fluid conduction.[5] In general, tank wall material should be selected to have a thermal conductivity less than that of the storage fluid.

[5] C. W. Miller, The Effect of a Conducting Wall on a Stratified Fluid in a Cylinder, Aerospace Industries Association of America (AIAA), 12th Thermophysics Conference, Report 77-792 (Albuquerque, NM, 1977), p 3; and T. D. Harrison, et al., Solar Total Energy Test Facility Project Test Result: High Temperature Thermocline Storage Subsystem, SAND 77-1528 (Sandia Laboratories, April 1978), pp 31-36.

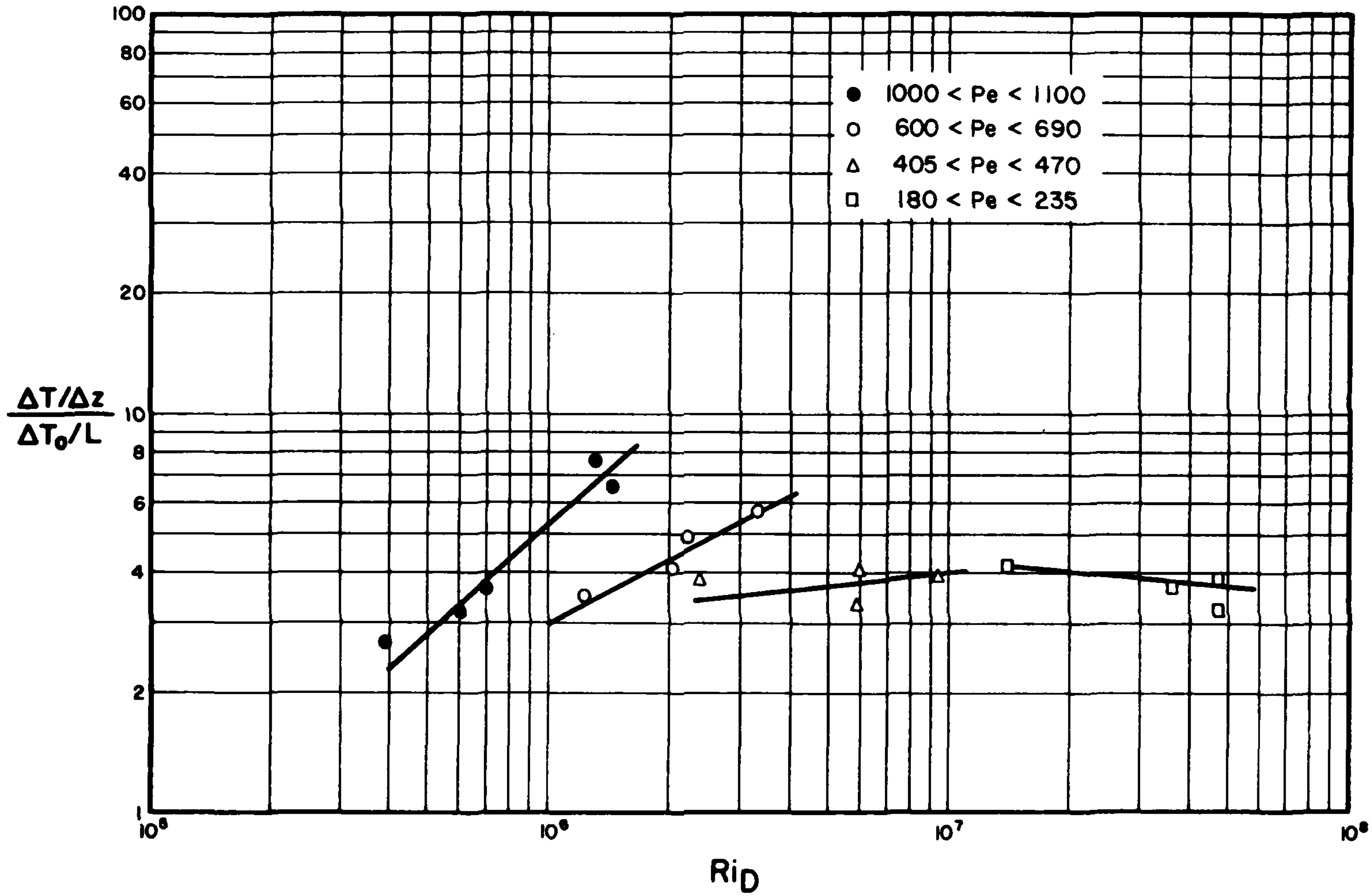

Figure 8. Sharpness of thermocline as a function of Ri_D and Pe for charging.

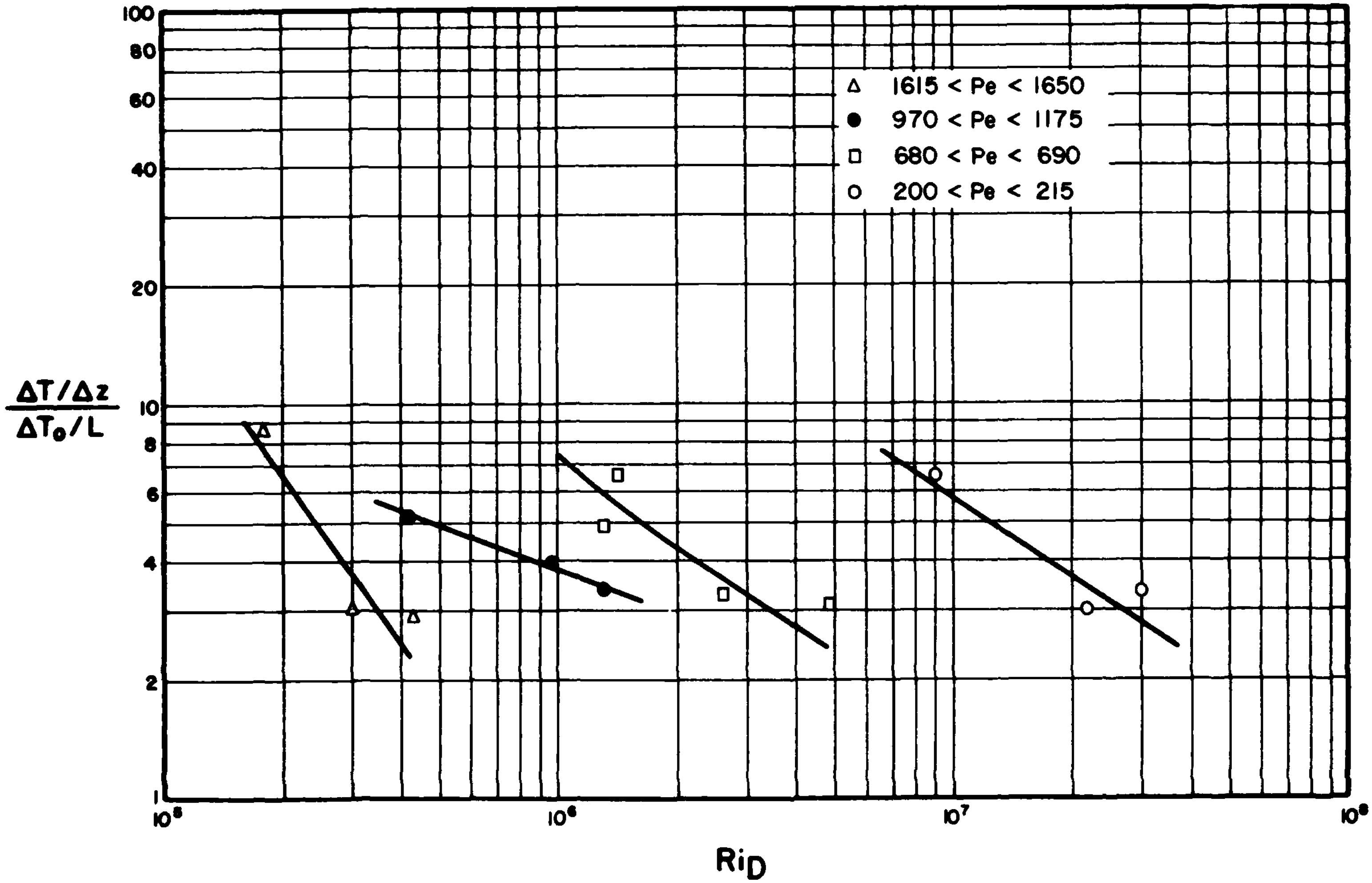

Figure 9. Sharpness of thermocline as a function of Ri_D and Pe for discharging.

3 THE EFFECT OF THERMAL STRATIFICATION ON THERMAL SYSTEM PERFORMANCE

General

The effect of stratification on thermal system performance is the subject of current research. The literature search conducted during this study indicated stratification improves system performance, but discovered no consensus as to the amount of improvement.

Mechanisms

Thermal storage stratification affects system performance through two mechanisms:

1. Higher charging and discharging rates
2. Constant outlet temperatures.

The following equations show how stratified storage allows for higher charging and discharging rates than mixed storage; i.e., for a mixed tank with constant temperature input and constant flow rate, the energy content as a function of time is

$$E = \Delta T_o MC_p \left(1 - e^{\frac{-\dot{m}t}{M}}\right) \qquad \text{[Eq 8]}$$

where:

E = energy content as a function of time

t = time

C_p = specific heat

$\dot{m}$ = mass flow rate (kg/s)

M = mass of storage fluid (kg)

For a perfectly stratified tank, the energy content as a function of time is

$$E = \Delta T_o \dot{m} C_p t \qquad \text{[Eq 9]}$$

The ratio E/E_{max} (where E_{max} is the minimum energy capacity of the storage) is shown as a function of the tank time constant M/m in Figure 10. Figure 10a shows that the stratified tank is fully charged in one time constant, whereas it takes about 4 to 5 time constants to fully charge the mixed tank.

The equation for discharging a mixed tank is:

$$E = \Delta T_o M C_p e^{\frac{-\dot{m}t}{M}} \qquad \text{[Eq 10]}$$

The equation for discharging a stratified tank is:

$$E = \Delta T_o \; C_p \; (M - \dot{m}t) \qquad \text{[Eq 11]}$$

Eqs 9 and 11 are plotted the same way in Figure 10b, which shows that the stratified tank is fully discharged in one time constant, whereas it takes about 4 to 5 time constants to fully discharge the mixed tank.

The rapid charge and discharge characteristics of stratified thermal storage will dynamically affect a system, but the degree of effect will vary from system to system. In general, there will be a decrease in the operating time of pumps and fans used to add or remove energy from storage. Also, the storage will be better suited to supply systems requiring high energy input rates.

The constant outlet temperature of stratified storage also affects system performance. Figure 11 shows the outlet temperatures of mixed and stratified tanks during charge and discharge. Note that the outlet temperature of the stratified tank remains constant through nearly the entire charge or discharge cycle, but the mixed tank outlet temperature varies.

Constant outlet temperature affects different systems in various ways, but, in general, when a system requires low supply temperatures (e.g., a solar collector) or constant high temperatures (e.g., an absorption chiller), stratified storage is better than mixed storage.

Effects on Solar Energy System Performance

The literature search conducted during this study indicated that research into system performance usually was done either by experimenting with actual solar energy systems or by using computer simulations. Both approaches have encountered problems.

Many actual system experiments, because of lack of understanding of the stratification problem, did not properly use the stratified storage energy system. In the case of computer simulations, the one-dimensional models generally used were not precise enough to model thermal storage.

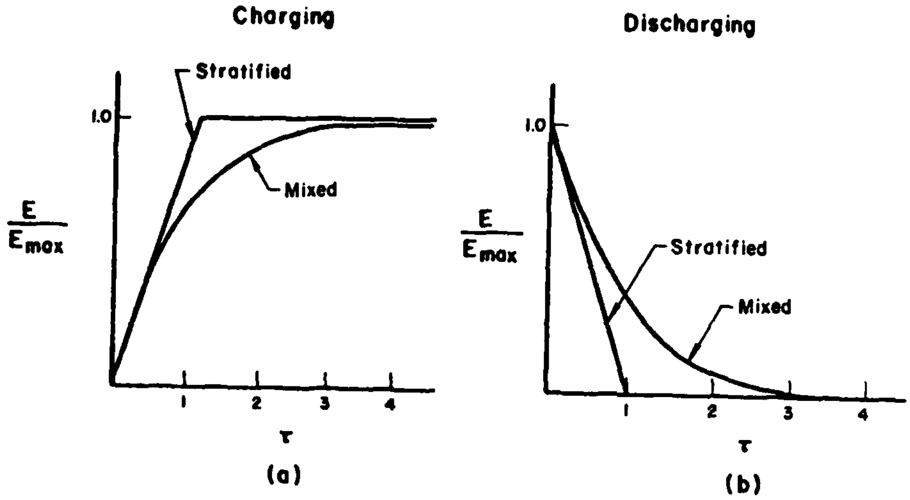

Figure 10. Charging and discharging rates of mixed and stratified storage.

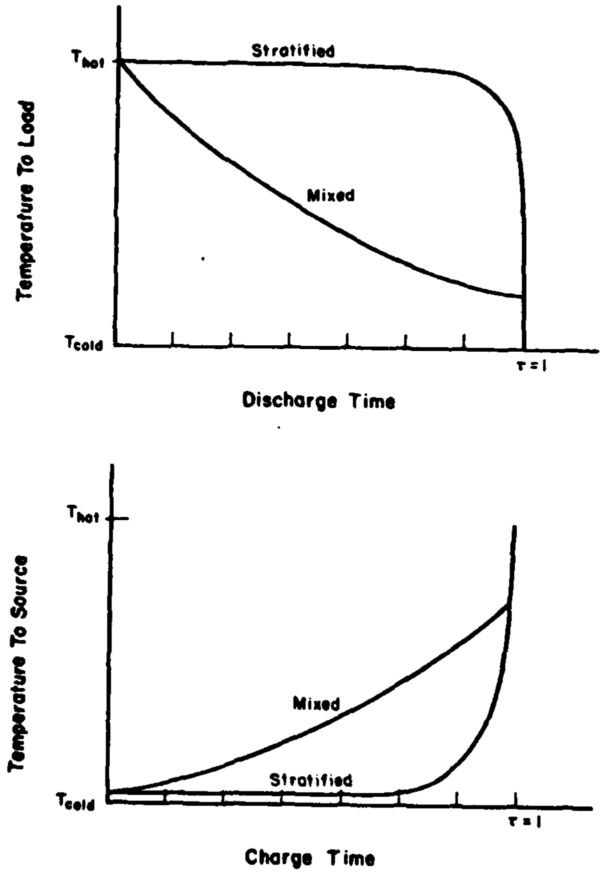

Figure 11. Output temperatures of mixed and stratified storage during charge and discharge.

Computer simulations using two- and three-dimensional models, while becoming very accurate, are not suited for detailed system simulation.[6]

Some results of recent research are summarized in Table 1. Table 1 shows that the amount of improvement in system performance varied from 0 to more than 30 percent. Figure 12 shows the improvement in system performance calculated using a modified TRNSYS[7] model with a lengthened time step.

In this simulation, the annual performance of a solar heating and cooling system was projected.

The storage tank model used was a six-segment tank similar to that used in past TRNSYS simulations with the exception of the use of a lengthened time step to calculate heat flow between each segment.

The lengthened time step was used based on comparisons of tank fluid temperature profiles predicted by the model for charging and discharging and experimental data from the same conditions. The best agreement was found when a lengthened time step was used.

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6 Personal communication between B. J. Sliwinski of the U.S. Army Construction Engineering Research Laboratory (CERL) and E. I. H. Lin of the Argonne National Laboratory, August 7, 1979.

7 "TRNSYS -- A Transient Simulation Program," American Society of Heating, Refrigeration, and Air-Conditioning Engineers (ASHRAE) Transactions, Vol 82, Part 1 (1976).

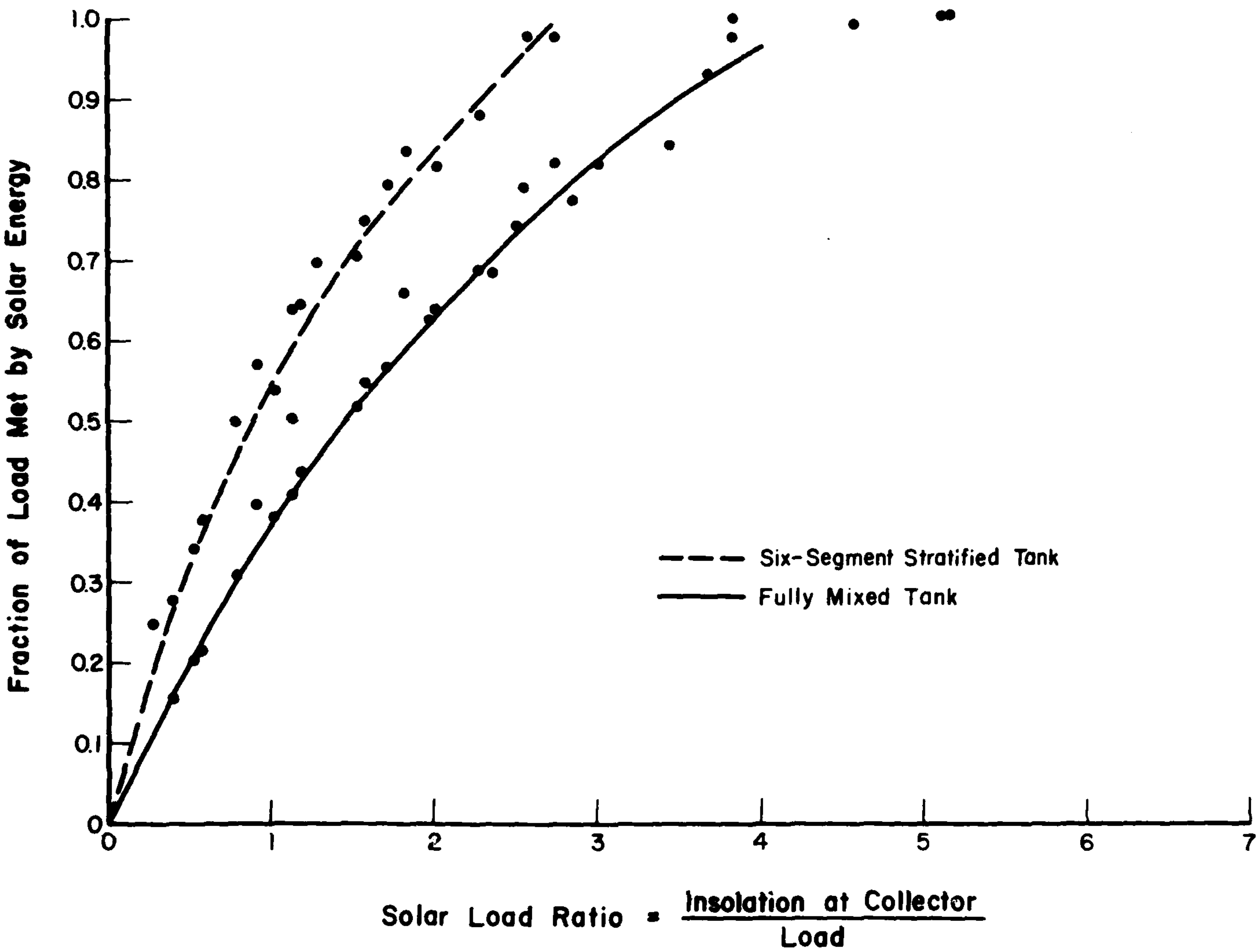

Figure 12. Improvement in performance of simulated solar heating and cooling system.

Table 1

Results of Research to Determine Effect of Stratification on Solar Energy System Performance

Researcher	Type of Study	Result	Reference
Namkoong	Experimental	No improvement	*
S. T. Wu	1-D TRNSYS simulation	6% improvement in collector efficiency	**
Y. NakaJima (et al.)	Simulation and experimental system	20-30% improvement in collector efficiency	***
Van Koppen	Experimental system	15% system improvement	+
E. H. Lin	3-D simulation analysis	30% system improvement	++
Walton & Sliwinski	1-D TRNSYS simulation with lengthened time step	15-20% system improvement	Results of the study documented in this report

* D. Namkoong, Temperature Distribution of a Hot Water Storage Tank in a Simulated Solar Heating and Cooling System, NASA Report TM X-73549 (National Aeronautics and Space Administration [NASA], Lewis Research Center, November 1976), p 7.

** S. T. Wu, The Theoretical and Experimental Study of Liquid Storage Tank Thermal Stratification for Solar Energy Systems, DOE Report No. COO/4479-1 (Department of Energy [DOE], February 1978), p 1.

*** Y. NakaJima, "Design and Performance of Thermal Storage water Tanks," Heliotechnique and Development, Proceedings of International Conference, Vol 1, Dhahran, Saudi Arabia (November 1975), pp 508-510.

+ C. W. J. Van Koppen, L. S. Fischer, and A. Dijkmans, "Stratification Effects in the Long and Short Term Storage of Solar Heat," Proceedings, 1978 meeting of Amercian Sec. International Solar Energy Society (ISES) (Denver, CO, 1978).

++ E. T. H. Lin, On Thermal Energy Storage Efficiency and the Use of COMMIX-SA for Its Evaluation and Enhancement, Solar Energy Storage Options Workshop, San Antonio, TX, 1979, pp 7-8.

4 CONCLUSIONS AND RECOMMENDATIONS

To assure efficient use of thermal stratification in liquid thermal storage, it is necessary to:

1. Introduce hot fluid at the top of the liquid storage tank and add cold fluid at the bottom of the tank.

2. With a cylindrical tank, use an L/D ratio ≥ 2.0.

3. Determine allowable fluid inlet velocities and temperatures from correlations in Figure 2 or Figure 5.

4. Use tank material that has a thermal conductivity less than that of the storage fluid.

Information about thermal stratification in liquid sensible storage is incomplete, but rapidly growing. Correlations have been developed which allow the designer to predict stratification occurrence and estimate the sharpness of the thermocline based on inlet and outlet conditions, fluid properties, and tank geometry. These correlations are not limited in application to solar energy systems. On the contrary, they are most applicable to conventional systems which have operating conditions similar to the experimental conditions from which the correlations were derived, i.e., constant input temperature and flow rate. They can also be applied to solar energy systems with the understanding that in solar energy systems, the tank input temperature from the collectors may not be constant.

The results of CERL's simulation and work in the literature indicate that the effects of stratification on the performance of solar energy systems are positive, showing an improvement in system performance of between 20 and 30 percent compared to a mixed tank system.

It is recommended that:

1. Systems using sensible heat storage should be designed to maximize stratification occurrence.

2. The response of stratified storage to time varying inlet temperatures which fluctuate above and below the temperature of the mixed region in the tank should be determined. In addition, there is urgent need for an accurate, quasi one-dimensional computer simulation model of stratification that can be used in system simulations to assess the impact of using stratification on the first cost of other system components. It is also important to determine suitable tank construction materials to insure low tank wall thermal conductivity.

NOMENCLATURE

L = Length of cylindrical tank (m)

D = Diameter of cylindrical tank (m)

T = Temperature (^{o}C)

η = Extraction efficiency (dimensionless)

g = Acceleration of gravity (m/s^2)

β = Volume expansivity (1/^{o}C)

V_i = Inlet velocity (m/s)

ΔT_o = Difference between inlet fluid and (^{o}C) initial tank fluid temperature

ΔT = Temperature difference across thermocline (^{o}C)

ΔZ = Thickness of the linear portion of the thermocline

C_p = Specific heat $\left(\frac{\text{joules}}{\text{kg}^{o}\text{C}}\right)$

$\dot{m}$ = Mass flow rate (kg/s)

M = Mass of storage fluid (kg)

Re_D = Reynolds number based on tank diameter bulk fluid velocity and average of hot and cold fluid temperature (dimensionless)

Pr = Prandtl number based on average of hot and cold fluid temperature (dimensionless)

V_D = Bulk fluid velocity based on tank diameter (m/s)

Re_d = Inlet Reynolds number

Gr_D = Tank Grashof number

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